Section of Psychiatry

President—William Sargant, M.A., F.R.C.P., D.P.M.

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The Brain as a Machine

By W. Grey Walter, M.A., Sc.D.
Burden Neurological Institute, Stapleton, Bristol

The title of this paper needs some explanation. Physiologists are accustomed to speaking of organs of the body with a definite article, assuming that all such organs are essentially similar, at least in a given species. Human brains may be an exception to this convenient rule, since, however we may choose to describe cerebral mechanisms, we must accept the evidence for personal variations, and these variations may be the main diagnostic character of highly evolved central nervous systems. In fact, psychiatrists and psychologists seem to imply something of this nature when they consider stereotypy as a sign of mental pathology. This is not to say that we cannot envisage *any* features common to all human brains but we should realize that whatever general picture we may form of the mechanics of brain function should include a high potentiality for individual idiosyncrasies.

The term "machine" also is liable to misinterpretation. We still tend to think of machines as though they were simple devices to amplify or conserve human muscles but a much wider definition is permissible and indeed essential if we are to consider more than the simplest aspects of mental behaviour.

The problems facing brain physiologists to-day are novel from the standpoint of classical biology, but they are not very unlike those familiar in other sciences. It is perhaps in meteorology that we find the closest resemblance to human neurophysiology, for in charting and predicting weather conditions a meteorologist must take into account the operation of a large number of interacting mechanisms, most of which are mysterious in their origin, though all are capable of exerting a major influence. There are serious and well-known risks incurred when prediction is based on empiricism, as anyone may quickly learn who plans a picnic in England in August, but many of these risks are due to the difficulty of distinguishing between large-scale and small-scale phenomena. Fine weather does not exclude the possibility of a local thunderstorm and, in fact, may even promote it. Similarly, in the physiology of the brain a high-grade normal level of function does not exclude the possibility of epileptic seizures; I have suggested elsewhere that the very refinement of normal discrimination in human brains may actually increase the possibility of convulsive breakdown (Walter, 1953).

The science of brain mechanics is at an awkward age of its development, relying still on classical terms but attempting to explore the frontier of evolution. We are in the pre-Newtonian age as it were, in which we can still argue amiably in terms of Cartesian vortices, though we may feel that at any moment a theory of Gravitation may destroy and simplify our web of fancy. If we find the associations of the word "machine" too instrumental, we should perhaps recall that the etymological meaning implies simply *a way of doing something;* we should be encouraged therefore to study behaviour rather than static structure even though we may still lack the tactical equipment for detailed analysis of complex systems.

The first question we should ask presumably is "What does the brain do?" A specific answer is not so easy to frame. One can say plausibly that the brain does everything we can think of, but this is of no great help in the design of an experiment nor presumably in the examination of a patient. If the question is differently phrased, the answer may be more explicit. Knowing from prior information that much bodily behaviour is implemented by interacting reflex circuits, we may legitimately enquire how complex a behaviour pattern can be formed by such a system of reflexive action. This enquiry yields immediate gain for we find ourselves transported into the new kingdom of cybernetics; the physiological reflex is an older and, I think, clearer term for what engineers call "servo" or "feedback systems".

The cybernetic approach to this domain is both practical and powerful. There is now a great mass of information on the nature and action of reflex systems in flesh and metal. The early notions of neurophysiologists are unconsciously embodied in many of them, but are extended in some to a degree which is hard to emulate in a physiological laboratory. Many of these intricate analyses can be demonstrated by the operation of working models, as has been shown by Ashby (1952), MacKay (1956), Shannon (1952), Uttley (1956), Wiener (1950) and myself. It can easily be seen, for example, that a system with only two reflexes can display an astonishing variety of apparently "purposeful" behaviour patterns.

Such a model can easily find its way around quite a complex world. It can avoid starvation or self-destruction, it can attain its sources of nourishment and refreshment, it displays a commendable moderation in its quest for gratification and avoidance of pain, it can solve without difficulty the dilemma of Buridan's ass, it behaves as if it could recognize itself as in a category different from all other structures and others of its own kind in a related category as well. We may conclude therefore that mere complexity of behaviour does not inevitably require more than an assembly of reflexive circuits—a spinal cord.

Careful observation of the antics of such models reveals that elaborate though the behaviour patterns may be—and they may be so bizarre as to deceive even a trained observer of animals—they display no modification by experience, and such modification we must put in a different class from mere complexity. Here again, study of model behaviour suggests that there is one class of adaptation still outside or below the domain of brain function; this is the type of improvement in performance by repetition which may be, and often is, achieved by a process no more sophisticated than the running in of a motor or the wearing out of a garment. Modification of this type is sometimes referred to as practice. The really interesting part of brain mechanics would seem to reside in the fine structure of that behaviour which we usually describe as thinking and learning. We may then consider specifically, how may human brains perform these functions? Again, study of working models of learning can assist us, for in their design the first article of the specification requires that they exert a power of selection over the information they receive. Like an ordinary radio set, a learning instrument is useless if its reception is too wide. It must be capable of tuning itself, as it were, to selected stations. The significance of a signal is not necessarily increased by multiplication of sources. We must therefore investigate the mechanism whereby a human brain can be tuned—or can tune itself—to those sources of information which it can identify as "wanted". As a first step in such a study, can we decide what the information is wanted for? We must suppose at least that, in general, it is wanted for the survival of both the individual and the species, but in either case the aim is essentially statistical or probabilistic. That is, the justification of an aim is not necessarily logical, though a logical goal may often be considered as a special case or part of a statistical situation.

This general notion, that the mechanics of brain function may be based on processes of statistical selection and reflexion, seems to me one of the most powerful of recent developments. It receives some support from the now familiar fact that logical reasoning, in the sense of syllogistic inference, is more easily and rapidly performed by standard computing machines than by human beings.

From the experimental standpoint, therefore, we are led to search for any part of the reflexive machinery likely to be connected with the powers of statistical selection and co-ordination which are suggested as essential in this hypothesis.

In many laboratories experiments are now in progress to study the details of learning in human beings with the modern aids of electro-encephalography and similar techniques. Although many claims have been made it still seems too early for evaluation of the results as a whole. There is some hope, however, of identifying certain features of a learning mechanism by specifications derived from theoretical analysis. Such considerations suggest that one of the most important aspects of such a mechanism would be a process analogous to that developed for automatic factories, whereby the flow of information and materials is co-ordinated in time so that the course of production is smooth and optimally related to the availability of components and the desirability of the finished article.

In a special sense, therefore, in the brain as in an automatic factory, time is of the essence. This does not mean merely that speed is of particular value, but rather that the sequence of events must somehow be preserved and classified. As a simple example, it is important for any creature to distinguish in some way between cause and effect, even in arbitrary terms We must be able to decide for ourselves whether lightning causes thunder, or thunder lightning or whether both have a common cause. Even this simple problem is not as easy to solve as it might seem, bearing in mind the widely different rates of transmission of light and sound in the outside world and the even more intricately variable rates of propagation of nerve impulses arising from the eyes and the ears in the nervous system. Zeus and Electricity are names not explanations. We should recall also that in the elementary working models of reflexive behaviour, the provision of an autonomous scanning mechanism offered an immediate solution for many elementary paradoxes of choice and symmetry. One part of our experimental work has accordingly been directed to the detailed analysis of those brain activities which seem to maintain a regular though adaptable rhythm, in the expectation that these may be found to be related to the mechanism of process control required for the systematic evolution of adequate statistical behaviour.

Until recently the methods of analysis were inadequate to provide confirmation or refutation of these hypotheses but we now have available a method for displaying and

measuring with a new order of accuracy the time and space relations of electrical events in the brain. The methods used heretofore have depended in the main upon some form of integration, averaging or summation to achieve the necessary degree of resolution. For example, in the Wave Analyser introduced many years ago (Walter, 1943) the various frequencies present in an EEG record are separated out and the abundance of each component is then added up over a period of ten seconds so as to provide a spectrum of the brain activity over this relatively long period. Similarly in the Toposcopic Display System first described in 1951 (Walter and Shipton, 1951), the rhythmic variations in voltage were transformed into changes of brilliance of a scanning vector on a cluster of 22 cathode ray tubes which were photographed in such a way as to permit summation of regular components by superimposition on the photographic emulsion. More recently (Shipton, 1957) the toposcopic method has been extended and modified so as to provide a high degree of resolution with respect to time in each of the 22 channels. This has been accomplished by introducing a spiral scanning time-base upon which are projected the variations in brilliance corresponding to brain activity. The speed of this time-base can be very accurately controlled and adjusted, and since the scale is coiled helically on the tubes the length of the exposure can be considerably prolonged. This provides what is termed "line-to-line correlation".

In effect, the display consists of 23 concentric circles, each representing one complete rotation of the cathode ray spot, of which the brilliance is modulated by the incoming signal. If the rotation rate is, for example, one revolution per second, then the complete tube would be scanned in 23 seconds. At the other extreme, if the scanning rate is 23 r/s, then the time to complete the picture would be one second. The presentation is illustrated diagrammatically in Fig. 1.

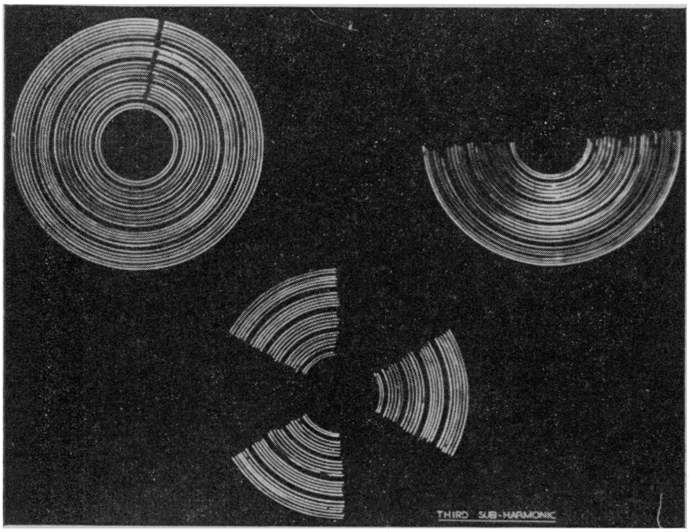
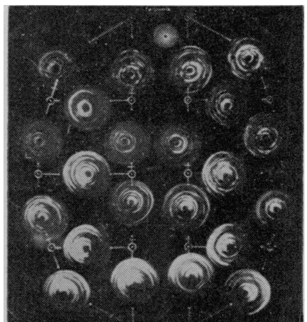
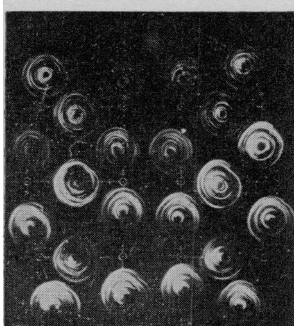


FIG. 1.—Diagrammatic examples of the helical-scan display system showing the 23 concentric circles. The gaps between the circles are to indicate time intervals during the exposure.



2A.



2B.

FIG. 2.—A, Alpha rhythms in normal subject at rest with eyes closed. The frequency varies from 8·3–9·6 c/s during the exposure but the phase relations in the various regions are consistent. B, Alpha rhythms in another normal subject with alpha frequency at 11·6 c/s again showing consistent phase relations which are similar to those in Fig. 2A although the frequency and distribution are different.

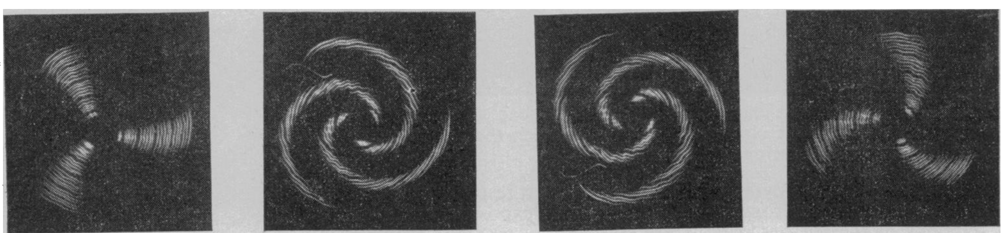
In this way records can be made either over a relatively long period with sacrifice of time resolution, or over a short period with a high degree of accuracy. For example, if it is desired to investigate the time relations of an alpha rhythm at 9 c/s the scanning rate can be set to nine revolutions per second and a device is available to lock the speed precisely to the frequency and phase of the incoming signal in one channel, which is then regarded as fiducial. Records obtained in this way are shown in Fig. 2, taken from two normal adult subjects. Here it is seen that the oscillatory waveforms of the alpha rhythms are represented as a group of black and white striped discs in the occipital region of the brain occupied by alpha activity; each line forming the disc is one "wave", and its length and brilliance indicate the wave

duration and amplitude respectively; in Fig. 2A the scanning frequency varied during exposure from 8·3 to 9·6 r/s. This was the range of variation in frequency of the alpha rhythm in the fiducial channel during this exposure, which lasted just under 2½ seconds. In each channel therefore there is a record of 23 waves and the time of occurrence of each wave in all channels can be seen at a glance, or, if desired, carefully measured. In this way can be obtained something approximating to an auto-correlation index for each channel and a cross-correlation index between channels. In this particular subject during this time it can be appreciated that this alpha rhythm is extremely regular in frequency and phase in each channel but the phase relations of the rhythm between channels are peculiar and intricate.

Fig. 2B shows a similar record taken from another subject whose principal alpha component was considerably higher in frequency—11·6 c/s. Here again there is a striking consistency in the time relations between channels. Furthermore, in spite of the difference in frequency and distribution of the alpha activity in the two subjects, there are marked resemblances in the phase relations between channels in both records. These records are two of a great many which exhibit unequivocal evidence that alpha rhythms do not occur precisely synchronously in all regions of the brain where they appear, but the time relations of their arrival may none the less be consistent over a period of several seconds, provided the mentality of the subject is undisturbed. These records were taken during rest, the subjects' eyes were closed and they had been asked to relax mentally as much as possible.

The next point to be established is that during the exercise of the mental faculties the consistent and coherent pattern of alpha distribution and time relations is elaborately but characteristically disturbed; this effect is exemplified in the next figure.

In order to follow the changes in alpha pattern associated with mental activity and stimulation, it has been found desirable to record at a scanning rate which is a sub-multiple of the rhythm to be investigated. This means that the exposure duration can be longer, while the estimation of time relations is correspondingly less accurate. When the scanning rate is exactly one-third of the frequency of the incoming rhythm, the records show patterns with three arms or petals which are perfectly straight, and, if the rhythm is entirely regular, with completely smooth edges. A test record of this type is shown in Fig. 3A. If, however, the frequency of the incoming signal is slightly greater than three times that of the scanning rate the three petals curl in a counter-clockwise direction (Fig. 3B). Contrariwise, if the signal is slightly less than three times the frequency of the scanning rate, the petals curl clockwise (Fig. 3C). The degree of curl—which can be seen at a glance—may be measured quite easily and indicates the precise frequency of the signal. In such an exposure the frequency of an alpha rhythm can be measured to an accuracy of 0·02 c/s (Fig. 3D). If measurements are made of each line, then it is possible to estimate the interval between individual waves as well as the over-all frequency. A record such as this displays just over seventy waves altogether, and if the activity is apparent in all channels, the total number of waves displayed in a single photograph is slightly over 1,500. The amount of information thus displayed is therefore very great and is certainly large enough to permit trustworthy computations of the significance of any changes that may be observed.



3A 3B 3C 3D

FIG. 3.—Test records showing the resolution of the display system run at one-third signal frequency. A, Signal at exactly three times scanning rate—9 c/s. B, Signal at 9·2 c/s. C, Signal at 8·8 c/s. D, Signal at 9·03 c/s.

Using this method it has been possible to demonstrate clear changes in alpha frequency and distribution during moderate mental effort, and a series of such photographs is shown in Fig. 4. The first exposure (A), shows the alpha distribution and frequency at rest and corresponds with the high speed record in Fig. 2A. During the next exposure the subject was asked to perform a simple mental calculation; the immediate effect of the instructions was to suppress the alpha activity in all but two channels in the right hemisphere which were connected antero-posteriorly between the central, temporal and parietal electrodes. Even

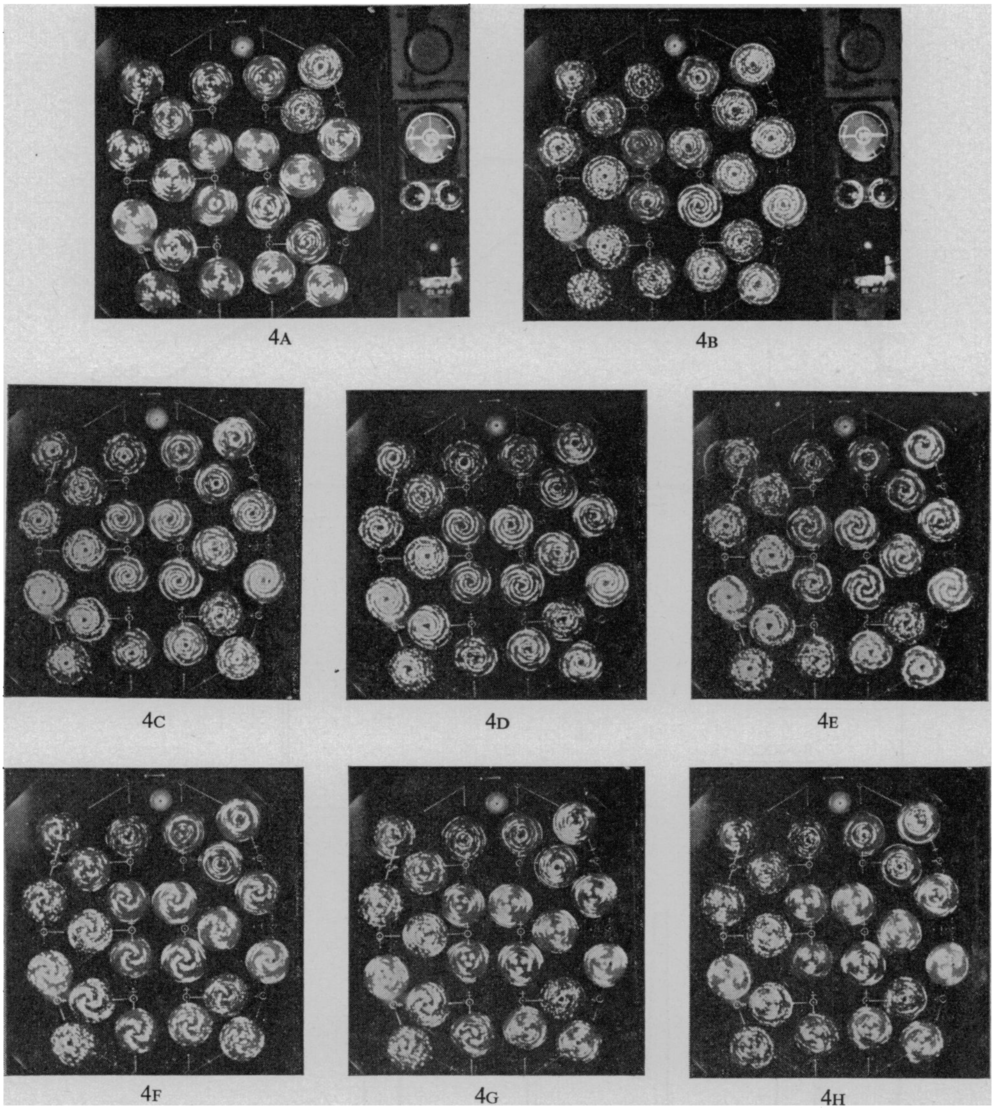


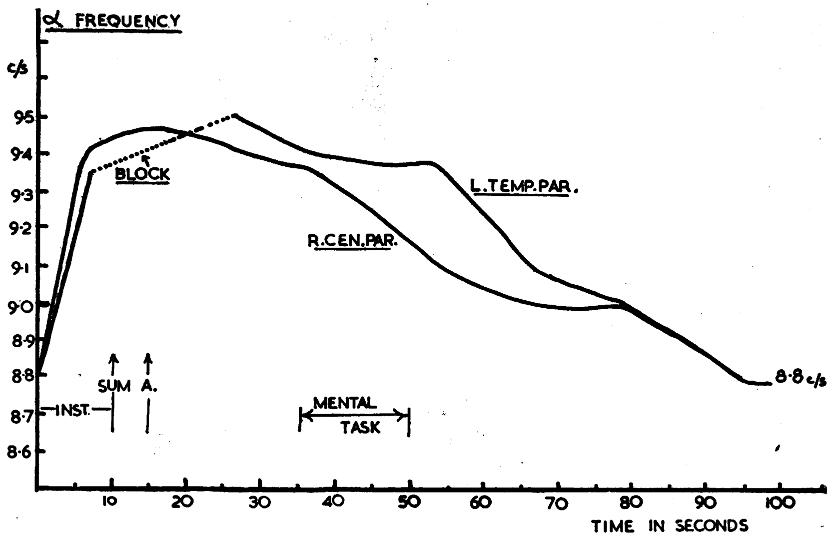
FIG. 4.—The effect of mental activity on alpha frequency and distribution in normal subject of Fig. 2A. The duration of each exposure was 8 seconds.

in these channels the rhythm was disturbed, as is shown by the curl of the three petals; the frequency in fact rose rapidly from 8·8 to 9·4 c/s.

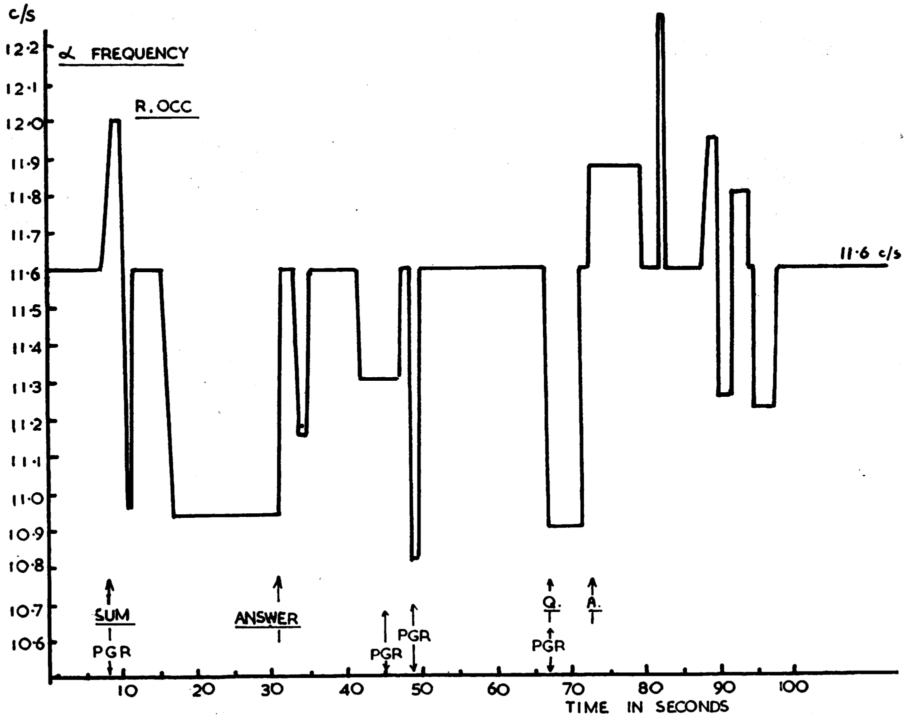
The other exposures in this series show a gradual return to the resting state. These are consecutive exposures, the whole set corresponding to a period of nearly two minutes. The solution to the first simple problem was given just before the third exposure, but the effect of the mental activity long outlasted the solution itself. The effect of the second task was much smaller and limited to the left side.

It can be seen that alpha activity gradually returned to the right hemisphere though at a higher frequency than before, while the left hemisphere remained affected until nearly the end of the period of observation and on this side, even when activity returned, it was still of considerably higher frequency than on the right side.

In the last exposure but one, the right hemisphere has returned to its original frequency and distribution, but the petals in the left hemisphere are still curling, indicating a slight but significant discrepancy in frequency between the two sides. In the last exposure the original pattern is restored to an extraordinary degree of concordance.



A



B

FIG. 5.—A, Graph of changes in the alpha frequency derived from Fig. 4. Note sustained rise in frequency of about 0·5 c/s and final return to original frequency. B, Alpha frequency changes in normal subject of Fig. 2B and Fig. 6. Note abrupt frequency shifts and return to original frequency. C, Alpha frequency changes in same subject as in A under the action of Meratran. The steady frequency has risen by 0·4 c/s and the rate of change during attention is abrupt and discontinuous, but again the frequency returns to precisely its original value.

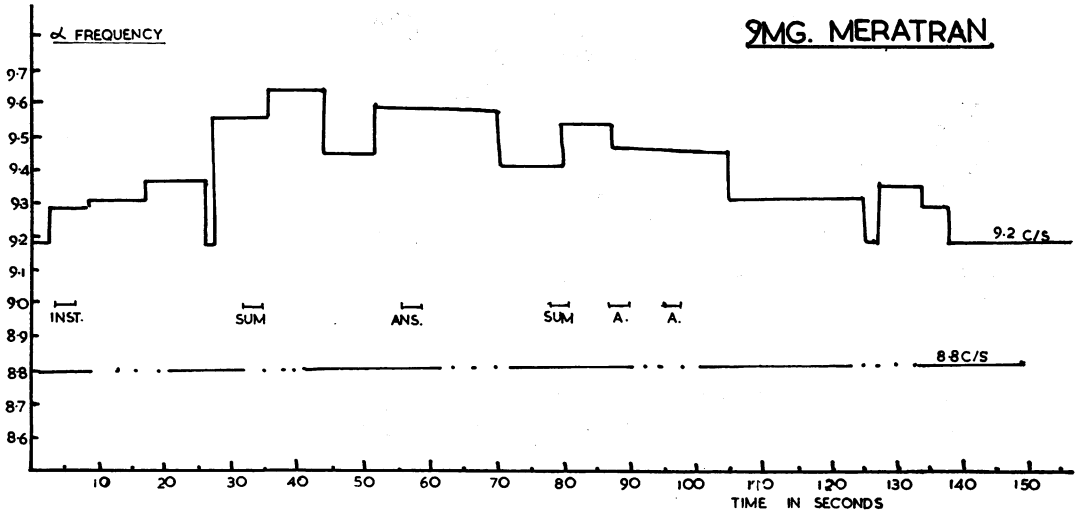


FIG. 5C.

In order to exhibit these changes in alpha frequency in a more conventional manner, a graph has been plotted (Fig. 5A) showing the rise and fall in frequency of the alpha component in the right centro-parietal channel during this very modest mental exertion and this is compared with the frequency change on the left side where, as already remarked, there was initially total suppression of rhythmic activity.

The most striking general inference is, that in spite of the pronounced and sustained alteration in frequency, the mechanism returned ultimately to precisely the same rate of discharge as before the experiment, even to an accuracy of one part in 100. It should perhaps be said again that a change of this order would be quite inappreciable in a primary record. It is just detectable with a wave analyser, but the interpretation of such variations in spectral distribution is inevitably ambiguous.

This set of records demonstrates that, as for example in the third exposure, a single quite restricted region of the brain can remain rhythmically active when all the rest is desynchronized. As a corollary, the two hemispheres, and even adjacent regions, may display complete autonomy of frequency and responsiveness.

There can therefore be no question of a supreme central pacemaker as has been suggested from time to time to account for the approximate synchrony and symmetry of spontaneous brain rhythms; nevertheless the degree of coherence and inter-channel correlation during rest suggests there is at times an appreciable tendency for some degree of synchrony. This tendency has been found to be a highly personal character and it may well be more important in relation to mentality than measurement of average or gross frequencies, since the way in which local rhythms fall into and out of step seems to be strictly related to the dynamic aspects of mental effort.

From the standpoint of mentality, consideration of these subtle changes in alpha pattern permits detailed study of the duration and extent of various types of attention and arousal. In the subject of the foregoing illustrations simple arithmetic problems provoked an effect lasting nearly two minutes, far longer than the time taken for the solving of the problem or the appearance of any overt action.

In the other subject, a normal adult woman, similar studies yielded quite different results. This subject has resting alpha rhythms with a mean frequency of 11·6 c/s in the occipital regions as shown in Fig. 2B. Fig. 6 shows the effect of mental activity in this subject. There is first a clear *slowing* of the activity in nearly all regions, then a return to the original frequency on the left side, then a further deceleration only in the left central region. Here again the pattern of response is absolutely typical of this subject in such conditions. A curve of the alpha changes in the right occipital region is shown in Fig. 5B. The whole character of the curve is clearly different from that of the first subject; there are abrupt shifts of frequency in both directions, mainly downward during periods of mental concentration. Most of these latter changes were associated with reduction of palmar skin resistance—psycho-galvanic reflexes. These records show particularly clearly the separation of the various alpha components in terms of both frequency and distribution. In other experiments, when this subject was threatened with punishment for failure to solve problems, the alpha frequency

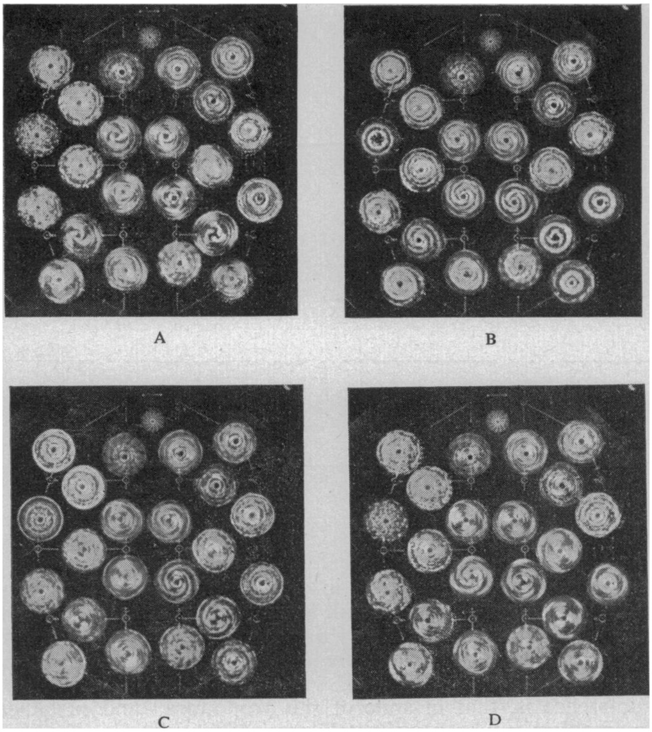


FIG. 6.—The effect of mental activity on alpha frequency and distribution in normal subject of Fig. 2B. A, shows the conditions during rest. B, Immediate slowing in all regions during the period of instruction. C, Desynchronization of the two hemispheres particularly in the parietal region. D, Desynchronization of the anterior and posterior regions in both hemispheres.

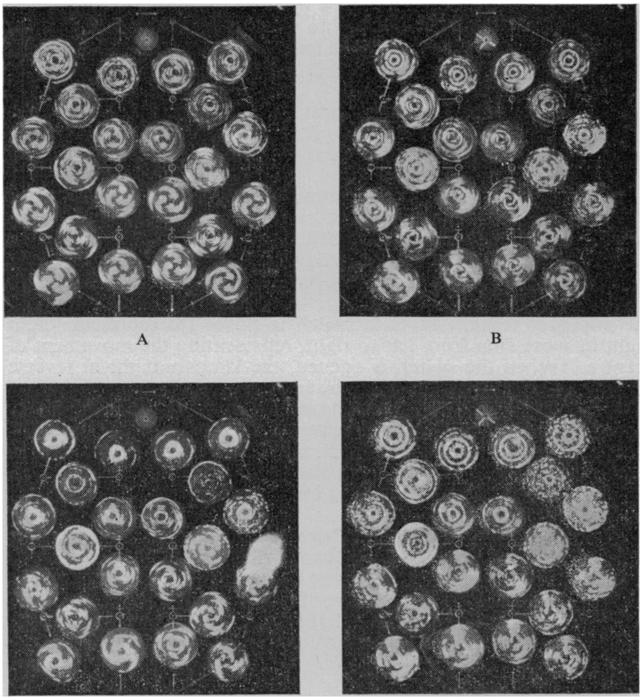
often *rose*, suggesting that the direction of alpha response may be a function of incentive quality.

For what it is worth—which may be little—these two subjects are very different in character. The first, who showed a sustained rise in alpha frequency, is original, speculative and persevering; the second, who displayed abrupt drops in frequency, is more receptive, conventional and erratic in her way of thinking.

As well as minute fluctuations in alpha frequency, other changes can be seen in these records. For example, in the subject of Fig. 4 an entirely new feature arose towards the end of the period of mental activity. The right frontal channel shows a component at about 3 c/s in the form of a single slow curl to the right in Fig. 4C and E; later, this component accelerated slightly (Fig. 4F) and then settled down to exactly 3 c/s (Fig. 4G). This was seen only during a period of mental activity and seemed to be associated with the return of the alpha rhythms to their resting state. It is tempting to consider this feature as an example of a restorative mechanism operating to maintain mental homeostasis.

The question naturally arises whether the fine structure of alpha responsiveness as illustrated in these cases is a permanent, unalterable feature of the electrical personality. In normal circumstances this seems to be the case. Even the most trivial details of the alpha patterns displayed by this means remain constant over a very narrow range in the same subject. None the less, by the action of certain drugs these characteristic features may be transformed or contorted. For example, the male subject of Fig. 4 was unobtrusively given a dose of 9 mg. of the drug *Meratran*, well known as an activating agent. The effect of this is shown in the graph in Fig. 5C where the changes in the alpha frequency in the right occipital region are plotted on the same scale as in Fig. 5A. These observations were made an hour after the unconscious ingestion of the drug; neither the subject nor his close associates were ever aware that he had taken it, possibly because he was very tired at the time. The effect on the alpha rhythms is clear and unequivocal as shown in the graph. There was a fairly rapid and sustained rise in mean frequency from 8·8 to just under 9·2 c/s and furthermore when requests were made to perform mental tasks as in the previous examination, the frequency changed abruptly and returned from time to time to its new resting level. The peak frequency was not greatly above that recorded during the normal period, 9·65 as compared with 9·45, but the general pattern of responsiveness was more irregular with sharp steps superimposed upon a sustained rise. It should be remarked that an alteration of this type would be only just perceptible as a long-term effect with a wave analyser, and the abrupt fluctuations in frequency would be quite undetectable even with this aid.

As another example of the action of drugs, the subject of Fig. 6 volunteered to take 100 micrograms of the hallucinatory drug LSD 25. During the action of the drug she reported vivid visual hallucinations for about four hours, but her personality remained unclouded and unperturbed, with only a minor persistent depression. In this case the effect of the drug, as reported by others, was again to raise the average frequency of alpha rhythms from a mean



A B C D

FIG. 7.—The effect on alpha frequency distribution of 100 gamma of LSD 25 in the normal subject of Fig. 6. A, Normal conditions before ingestion of drug. B, Comparison of normal alpha rhythms and flicker response. C, Acceleration of alpha frequency from 11·6–12·7 c/s and desynchronization of adjacent regions in the left hemisphere. D, Flicker responses evoked during action of drug.

of 11·6 to 12·7, which is considerably higher than the top frequency reached momentarily during mental activity in the normal state. Apart from this clear change in average frequency, there is a very marked alteration in the distribution and concordance of the various activities. In the normal state illustrated in Fig. 7A, the 11·6 c/s rhythm is everywhere synchronous and, in fact, the details of the various patterns are remarkably similar, even as far as the anterior frontal regions. Under the action of the LSD, however, the precise frequencies are quite different even in adjacent regions (Fig. 7C). For example, in the left occipital derivations, the parieto-occipital channel shows a clockwise curl indicating that the frequency is about 12·5 c/s whereas the near-by temporo-occipital channel shows a counter-clockwise curl indicating a frequency of about 12·8 c/s. This effect was observed during the greater part of the period of drug action and seemed to coincide with the phase of maximum hallucination. It does not seem unreasonable to suppose that this degree of disintegration in a subject whose alpha rhythms are normally closely synchronized may reflect a state of mind in which exogenous and endogenous stimuli are unusually dissociated. In Fig. 7B and D are examples of the effect of LSD 25 on the responses evoked by pattern flicker in the same subject.

These brief sketches from a physiologist's notebook are not intended to suggest that we are approaching anything like comprehension of the mechanics of mentality—they are merely illustrations of the evidence already to hand that there exist in the brain mechanisms which have that degree of order and consistency which we habitually associate with machines.

Earlier on, I pointed out the importance of "timing" in a mechanism such as we postulate in the brain. The extreme regularity and stability of the alpha processes in the subjects we have studied—and their subtle variations during thinking—suggest that there is here available a mechanism for preserving and comparing the sequence of events in time. Our present work is directed to investigating how these mechanisms operate during the course of learning and forgetting in human subjects. Such a study is unavoidably lengthy and elaborate, but there is already reason to hope that within a few years we shall be able to formulate a more detailed specification of brains as machines.

The observations reported here are the outcome of technical research and development by my colleagues, Mr. Harold Shipton and Dr. Raymond Cooper. It is a pleasure to acknowledge my gratitude to them and also to my friends who have acted as very patient subjects in these experiments.

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Dr. W. Ross Ashby: Until a few years ago we all thought we knew what we meant by a "machine"; our experiences with the alarm-clock and the typewriter seemed to provide an adequate basis for considering what a machine could or could not do. As a result, we tended to expect that no machine could do the complex and subtle things that the brain does. Whenever some mechanism was produced that did something brain-like we were surprised.

Those days are gone. To-day it is known that if any action or form of behaviour can be unambiguously specified, then there is undoubtedly a mechanism that can do it. For to-day there exists a well-defined routine by which the specification of the behaviour can be re-coded into the specification of a machine that will produce it.

To illustrate this fact, and to make the statement a little more convincing, I have here (Dr. Ashby demonstrated the machine to the meeting) a simple machine that can be so used to provide any demanded behaviour, provided that the behaviour is objectively defined and that it does not exceed the machine's capacity in size. I have chosen three forms of behaviour for demonstration. The machine is controlled by switches, which form its "input", and displays its behaviour on a row of lamps, which light and go out.

The first behaviour is simply the pupillary reflex. When a switch is closed (to represent "light shining into the eye"), the lamps light in succession from left to right, representing the movement of one edge of the iris towards the centre. When the switch is opened, the lamps unlight in reverse order. In this example the "contraction" is sustained as long as the switch is closed.

A second demonstration (after change of some linkages) shows the same reflex when the contraction is not sustained. Closure of the switch results in the lamps lighting across from left to right as before, but the lighting is not sustained, and one by one the lamps go back, from right to left, into the unlit state even though the switch is kept closed. Keeping the switch closed gives no further action. If, however, the switch is opened (representing "light no longer shining into the eye") and then re-closed, the "reflex" will appear again, but again fail to be sustained.

A third demonstration showed a behaviour with "memory". Before the switch is closed, nothing happens on the lamps. When the switch is closed, again nothing happens. The switch can then be opened again (i.e. the "stimulus" removed) and still nothing happens; but later, after a definite period of delay, the lamps light and show a characteristic (arbitrary) piece of behaviour.

These demonstrations *prove* nothing, but they illustrate the fact that the modern logic of mechanism (Ashby, 1956) is able to handle questions of the relation between structure and function with a completeness impossible ten years ago.

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Dr. D. M. MacKay: I should like to make a general remark on the limited usefulness of conventional quantitative mathematics in the theory of the nervous system, for I feel that Dr. Grey Walter may have been unduly apologetic in disclaiming an understanding of it. There are of course quantitative questions, concerning the information-capacity of a synaptic link or of a receptor organ, for example, to which one seeks numerical as well as qualitative answers. But I believe that the bulk of questions of psychiatric interest are organizational ones, demanding precise expression not in numerical terms but in the qualitative language of information-system theory.

The importance of this language lies, I think, in its ability to serve as a link between psychological concepts on the one hand and physiological concepts on the other. Hypotheses framed in terms of information-flow can, in principle, have implications—and so be tested—at both the psychological and the physiological level. With the development of even a skeleton "information-flow-map" of the nervous system, data expressed in the one language could begin to suggest hypotheses in the other (MacKay, 1954), so increasing the efficiency of diagnostic tests, and by the same token refining progressively the flow-map itself. What I am suggesting is quite different from the construction of a working model; for to those who understand a theoretical map a model shows little, while to those who do not, it often seems to show more than it should.

My point is that for the understanding of the general principles of such "maps" no high-powered mathematical training is required. The concepts involved (information-flow, control, selection, suppression, and the like) are more akin to those of administrative organization than to those of algebra. Inevitably, the "higher reaches" of this discipline, like any other, have their sophisticated techniques, and there is no royal road to their mastery. But I think it important to disclaim, as a theorist, any suggestion that psychiatrists lacking conventional mathematical training must find the theory of brain organization inscrutable, and must look to demonstrations by electronic "black boxes" as a less inscrutable substitute for understanding.

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Dr. F. H. George: The importance of the models which have been discussed lies largely in their value as research tools. They are more useful to some than to others; I myself think there is a great deal to be said for the use of mathematical models. Certainly they would easily include the sort of models so far built in hardware. I emphasize this only to try and avoid any false impression at a time when mathematical biology is rapidly coming of age.

I would also like to emphasize that I believe that discussions on whether or not machines can be made to think are liable to prove fruitless.